Realistic Performance Measurement for Body-Centric Spatial Modulation Links

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Abstract—**Spatial Modulation is a new transmission mode which increases spectral efficiency by employing information-driven transmit antenna selection. This performance is realized at a reduced hardware complexity and cost because only a single radio-frequency transmit chain is necessary. A measurement campaign is performed to assess the characteristics of spatial modulation over a body-centric communication channel, transmitting from a walking person with textile antennas integrated into the front and back sections of a garment, towards a base-station in realistic conditions. In the transmitted frames, additional spatial multiplexing as well as space-time coded data blocks are included. The off-body communication link is analyzed for line-of-sight as well as non line-of-sight radio wave propagation, comparing the characteristics of the different transmission modes under equal propagation conditions and for an equal channel capacity of 2 bit/s/Hz.**

Index Terms—**Spatial modulation (SM), textile antenna, body-centric, experimental results, MIMO.**

I. Introduction

Spatial Modulation (SM) is a novel transmission mode, representing a low-complexity spectral efficiency enhancing technique. To perform SM, multiple transmit antennas are switched in a single hardware transmit chain. When generating SM, the antenna switch is controlled symbol by symbol, based on a stream of additional information bits to be transmitted, supplementing the information already encoded by the modulator in the transmit chain. Therefore, the selected antenna number, possibly differing for each transmitted symbol, conveys extra information on top of the modulated symbols, providing N extra information bits for a set of 2^N transmit antennas. The absence of separate transmit chains per antenna significantly reduces the complexity, size and cost of a multi-antenna transmitter. In this paper, SM is employed for a 2-antenna system with biphase-shift keying (BPSK) modulation, achieving 2 bit/s/Hz by transmitting 1 bit/s/Hz BPSK and adding another 1 bit/s/Hz by switching between two transmit antennas.

In literature, several articles discuss the characteristics of SM, based on analytical derivations and simulations. The properties of SM are well documented and characteristics of SM and Alamouti coding are compared in [1]. A performance analysis in [2] indicates that SM with optimal detection outperforms the Vertical-Bell Laboratories Layered Space-Time (V-BLAST) architecture. Further research into SM, describes Trellis coded SM [3] and Space-Time Block Coded SM [4], leading to performance enhancements. Most recently, in 2014, Quadrature Spatial Modulation (QSM) was proposed in [5], enhancing the throughput of SM, as well as Differential Spatial Modulation (DSM) in [6], to further reduce system complexity.

In contrast to the extensive theoretical evaluations, only three papers document performance measurements for this new modulation mode. A practical implementation on an NI-PXIe-1075 chassis for a fixed line-of-sight (LoS) setup is documented in [7]. In the experiment described, a realistic transmission is performed, including synchronization and channel estimation issues. However, the LoS setup represents an office desktop to desktop link over just 2.2 m distance. Moreover, the behavior for this static setup is dominated by power imbalance between the channels, as visible in the non overlapping cumulative distribution functions (CDF's) presented by the authors.

The Bit Error Probability of SM over measured indoor channels, including NLoS as well as LoS conditions, is documented in [8]. In the latter publication, no real SM transmission is performed, as calculations are performed based on network-analyzer measurements. Similar experiments, measuring outdoor MIMO channels and employing the data for simulation of SM, are documented in [9]. These two articles provide SM characteristics in case of perfect channel state information, without channel variation during the transmitted frames.

In comparison to [7] and [8], further experiments are necessary to reliably assess the practical performance of SM. Experiments documented in [8] for an array of omnidirectional receive antennas deployed at a large number of different indoor locations indicate a better performance of SM for NLoS links compared to LoS links, thanks to the reduced correlation of the signals. However, for off-body transmissions from mobile people, shadowing by the body substantially reduces the antenna correlation for both LoS and NLoS scenarios. Therefore, SM is a promising modulation technique for off-body communication in both radio propagation environments.

The performance of SM also depends on the accuracy of the channel estimates at the receiver. Channel estimation errors compromise the receiver's ability to take a correct decision about the transmit antenna used for each symbol, for channels having only limited differences in amplitude and phase, even at high signal-to-noise ratios. As movement is continuously present during the measurement, a significant influence of channel variation exists, even during the transmitted frames. The channel variation limits the performance of the demodulation, but the results correspond to a fully realistic transmission.

In this paper, measurements are performed to assess the practical performance of SM for off-body wireless communication from a walking person towards a base-station, in LoS as well as NLoS conditions. The person is equipped with textile antennas integrated into the front and back sections of his garment.

For comparison to well-known modulation methods, Spatial Multiplexing (SMX) and Space-Time Code (STC) transmissions are performed within the same frame, evaluating the performance of the three modulation forms included under similar channel conditions.

The measurement setup is presented in Section II, whereas the statistics of the measured signals are discussed in Section III. The resulting Bit Error Rate (BER) characteristics as a function of Signal-to-Noise Ratio (SNR) for SM, SMX and STC are documented in Section IV and after a discussion in Section V, the conclusions are listed in Section VI.

II. Measurement setup

For the measurement in the 2.45 GHz band, a person is equipped with dual-polarized textile antennas [10] integrated into the front and back sections of his jacket. The radiating textile patch in these antennas is excited with respect to a textile ground plane, resulting in a hemispherical radiation pattern, efficiently directing the transmitted power away from the body and achieving a measured boresight forward gain of 6 dBi [10]. The antennas are placed in the center of the front and back of the torso, allowing maximum decorrelation of the signals and effectively mitigating body shadowing for the STC transmission [11].

The static base-station receiver employs a vertical uniform linear array (ULA) composed of four antennas, described in detail in [12]. The center-to-center distance between the elements is 0.75λ at 2.45 GHz and mutual coupling is lower than -15 dB for each combination of elements.

The measurement setup is illustrated in Fig. 1. The transmit antennas are directly connected to the Signalion HaLo430 wireless testbed, producing all the modulations considered. SM is achieved by transmitting symbols only from one TX port at any given symbol time, generating the same SM signal as when employing a TX switch.

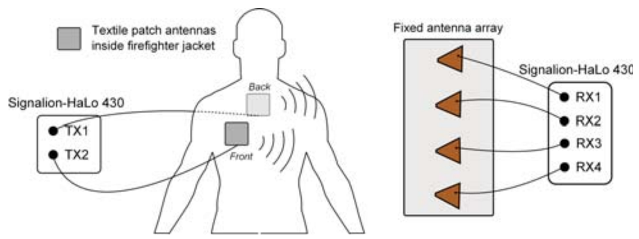

Fig. 1. Setup of the measurement system

The mobile user is performing a random walk in LoS as well as NLoS propagation environments, including reorientation but limiting the area covered to avoid excessive variation in path loss. Although a substantially larger range is possible, the measurements are performed at a distance of 10 m between transmitter and receiver, to achieve a high signal-to-noise ratio, allowing BER analysis by means of the addition of noise in the post processing stage. The sum of the transmitted powers on front and back antennas is 10 mW for the NLoS measurement and 1 mW for the LoS experiment.

The transmission is organized as shown in Fig. 2. Each transmitted frame consists of 300 BPSK-modulated pilot symbols for each transmit port, followed by three blocks of 300 data symbols formatted in each transmission mode under study, being SM, STC and SMX in this case. The frames of 750 μs duration are continuously transmitted, separated by a transmit gap of $640 \mu s$, to allow the assessment of the noise power at the receiver during the time in between the transmitted frames. The power of the transmitted pulses is chosen such that the sum of the transmitted powers on both antennas is equal for each transmission mode.

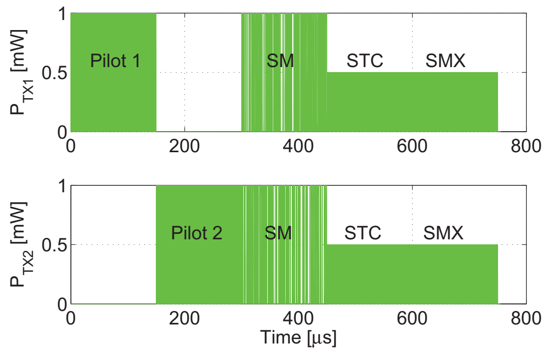

Fig. 2. Structure of the transmitted 750 μs frame, power of the transmitted pulses for the LoS link; total power equals one milliwatt for each symbol

The transmissions are performed on the front (TX1) and back (TX2) antennas, at 2 bits/s/Hz for each of the following transmission modes:

- SM: Spatial Modulation in BPSK
- SMX: Spatial Multiplexing in BPSK
- STC: Alamouti Space-time block coding in QPSK

When employing SM, symbols are transmitted in BPSK modulation on only one antenna for each symbol duration, switching between front and back antennas according to the content of the additional information bits to be conveyed. In SMX, two independent BPSK data streams are transmitted on both antennas. For STC, the data is Alamouti encoded and QPSK modulation is chosen in order to obtain the same spectral efficiency of 2 bits/s/Hz. At the receiving side, a Signalion HaLo430 wireless testbed is connected to the four ports of the textile antenna array. Signals are sampled on all ports and transferred to Matlab for processing.

STC is detected by the 'Two-Branch Transmit Diversity with M Receivers' method proposed in the classic paper by Alamouti [13]. SM and SMX symbols are recovered by means

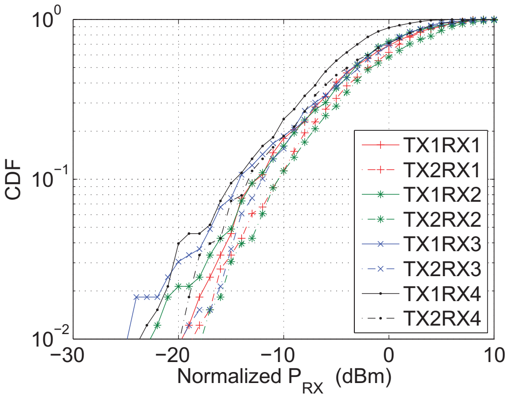

Fig. 3. CDFs for the normalized received power per NLoS channel

of the optimal Maximum-Likelihood (ML) receiver,

$$\left[\hat{l}_t, \hat{s}_t\right] = \underset{\substack{l \in \{1,2,\dots N_t\} \\ s \in \{s_1, s_2, \dots s_M\}}}{\operatorname{argmin}} \left\{ \|\mathbf{y} - \mathbf{h}_l s\|_F^2 \right\}, \qquad (1)$$

where $\mathbf{y}$ is the $N_r \times 1$ received signal vector, $\mathbf{h}_l$ the channel vector corresponding to the l-th transmit antenna and s is the transmitted symbol. The estimate $\left[\hat{l}_t, \hat{s}_t\right]$ provides the detected transmit antenna number and symbol, respectively.

III. Statistics of Measured Signals

Based on the pilot symbols, a statistical analysis is performed documenting the channel behavior. The CDF and signal envelope correlation properties are displayed for the NLoS as well as LoS links.

A. NLoS link

The cumulative distribution function for the received signal powers in the NLoS link is displayed in Fig. 3. Here, the signal powers are normalized using the same factor for each channel, in order for the average received power on all channels to be 0 dBm. The CDF characteristics largely overlap, illustrating limited channel imbalance, for the different receive channels as well as for the front (TX1) and back (TX2) transmit antennas. Fading occurs over a 35 dB range, as is expected for NLoS communications under Rayleigh fading conditions.

The envelope correlation for the signals is shown in Table I. A positive but limited correlation exists for signals transmitted by the same transmit antenna and received by different elements of the receiving array. According to [13], envelope correlation coefficients below 0.7 indicate that a significant diversity gain is possible. All correlation values between signals originating from front and back transmit antennas are negative, illustrating the complementarity of those antennas and their ability to counter shadowing by the body when their signals are combined.

B. LoS link

The CDF curves and envelope correlations for the signals in the LoS link are shown in Fig. 4 and Table II, respectively.

TABLE I
Signal Envelope Correlation matrix for the NLoS link

TX1 (Front)				TX2 (Back)			
RX1	RX2	RX3	RX4	RX1	RX2	RX3	RX4
1.00	0.39	0.35	0.27	-0.33	-0.28	-0.27	-0.30
0.39	1.00	0.24	0.23	-0.26	-0.25	-0.26	-0.30
0.35	0.24	1.00	0.34	-0.27	-0.27	-0.17	-0.24
0.27	0.23	0.34	1.00	-0.19	-0.23	-0.14	-0.20
-0.33	-0.26	-0.27	-0.19	1.00	0.45	0.33	0.36
-0.28	-0.25	-0.27	-0.23	0.45	1.00	0.37	0.39
-0.27	-0.26	-0.17	-0.14	0.33	0.37	1.00	0.42
-0.30	-0.30	-0.24	-0.20	0.36	0.39	0.42	1.00

TABLE II
Signal Envelope Correlation matrix for the LoS link

TX1 (Front)				TX2 (Back)			
RX1	RX2	RX3	RX4	RX1	RX2	RX3	RX4
1.00	0.21	0.18	0.24	-0.06	0.01	-0.07	-0.11
0.21	1.00	0.13	0.15	-0.10	-0.05	-0.07	-0.20
0.18	0.13	1.00	0.30	-0.09	-0.02	-0.15	-0.08
0.24	0.15	0.30	1.00	0.01	0.03	0.01	-0.04
-0.06	-0.10	-0.09	0.01	1.00	0.47	0.29	0.19
0.01	-0.05	-0.02	0.03	0.47	1.00	0.47	0.23
-0.07	-0.07	-0.15	0.01	0.29	0.47	1.00	0.43
-0.11	-0.20	-0.08	-0.04	0.19	0.23	0.43	1.00

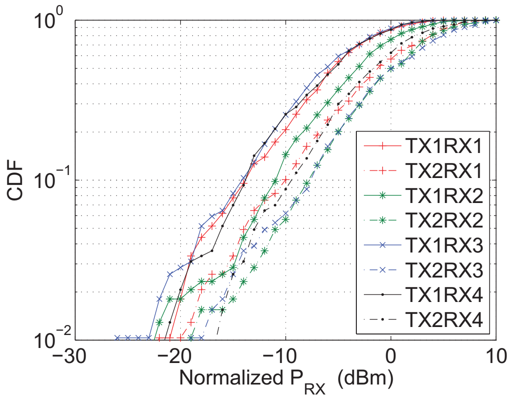

Fig. 4. CDFs for the normalized received power per LoS channel

Clearly, the shadowing by the body has a large influence on the CDF characteristics, where a signal variation similar to the NLoS link is observed. The difference in signal level produced at the receiver by a front or back antenna can be very large in LoS conditions, due to the continuous reorientation of the mobile user during the random walk.

Correlation values are also very low, indicating that multipath propagation plays an important role, even in LoS conditions. Note that during the random walk, front or back antennas will often not be oriented towards the receiver. Therefore, they will be shadowed by the human body for a large part of the measured frames. Hence, signals are frequently received via reflected paths. The correlation between signals originating from front and back antennas is often negative but not to a similar extent as in the NLoS scenario, suggesting the presence of specular reflections providing strong signals from antennas oriented away from the receiver.

IV. Bit Error Rate for SM, SMX and STC

In contrast to network-analyzer based measurements described in [8] and [9], this experiment realizes a true wireless data link requiring amplitude, phase and frequency-offset estimation, including estimation errors. In addition, the off-body measurement with a walking person results in a degree of channel variation during the transmission of the frame, generating varying Doppler shifts. The accuracy of the channel estimates is important for a reliable demodulation. BER characteristics are obtained by means of the addition of complex Gaussian noise to the recorded signals in the post-processing stage. Yet, they still correspond to a realistic demodulation of the data transmission.

A. 2×1 *MISO link*

Fig. 5 displays Bit Error Rate (BER) characteristics as a function of the received SNR, for reception by the top antenna element of the array, corresponding to receive channel RX1. Remember that QPSK modulation is employed for STC, whereas BPSK is used for SMX and SM, in order to achieve equal spectral efficiencies of 2 bits/s/Hz for all transmissions.

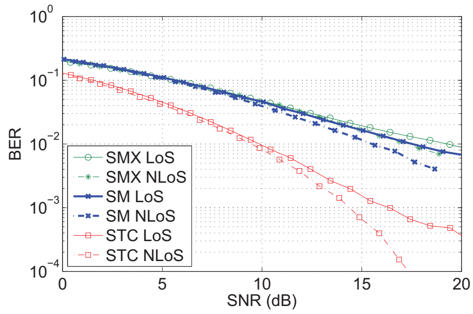

Fig. 5. BER as a function of SNR for the 2×1 links

STC achieves a much better BER performance than SM and SMX, thanks to the 2nd-order transmit diversity, a behavior that is similar for the LoS and NLoS links. Without diversity, a very high SNR is necessary for the SM and SMX links in indoor fading propagation conditions. To obtain an acceptable BER at a realistic SNR for the latter modulations, receiver diversity must be employed.

B. 2×2 *MIMO link*

Fig. 6 displays Bit Error Rate (BER) characteristics as a function of the received SNR, for reception by the two outer antenna elements of the array, corresponding to the receive channels RX1 and RX4. The characteristics are shown as a function of the average received SNR per input antenna. Therefore, they exhibit diversity gain as well as array gain.

For SM, a BER $\approx 10^{-3}$ is obtained at an SNR $= 15$ dB and an SNR $= 16.5$ dB for the NLoS and LoS links, respectively. The slope of the characteristics corresponds approximately to 2nd-order diversity for uncorrelated Rayleigh fading channels.

SMX achieves a BER $\approx 10^{-3}$ only at SNR ≈ 20 dB, for both propagation environments. STC requires an SNR of only 12.2 dB for the same BER.

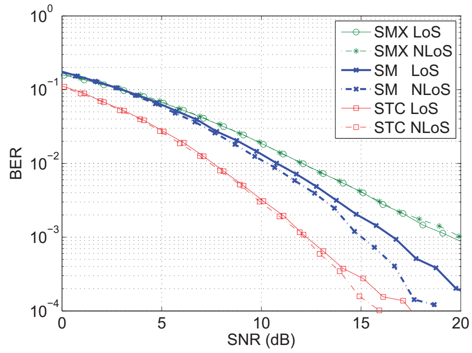

Fig. 6. BER as a function of SNR for the 2×2 links

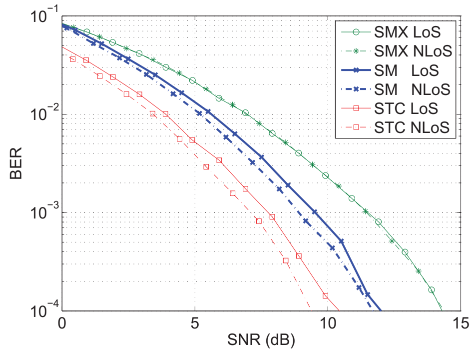

Fig. 7. BER as a function of SNR for the 2×4 links

Comparing these results to literature, in [7] a huge SNR is required to achieve an acceptable BER for SM on a 2×2 link at 2 bits/s/Hz in a Ricean fading channel with $K = 33$ dB. The experimental results are dominated by power imbalance between the channels. The off-body communication measurements presented here are very different, as 35 dB fading and shadowing fluctuations are present on significantly decorrelated received signals.

C. 2×4 *MIMO link*

Employing all four receiving elements provides more array and diversity gain, as well as richer channel information to correctly detect the transmit antenna in SM, or to separate the parallel streams in SMX. The BER characteristics in Fig. 7 illustrate the further performance enhancement obtained for the 2×4 link, compared to the 2×2 link.

A BER $\approx 10^{-3}$ level is now achieved by SM at SNR $=$ 8.9 dB and SNR $= 9.5$ dB, for NLoS and LoS conditions, respectively. A gain of 6.1 dB and 7 dB, for NLoS and LoS propagation, respectively, is obtained by switching from a 2×2 to a 2×4 configuration.

SMX achieves the same BER at SNR ≈ 11.5 dB for both scenarios, whereas STC requires only an SNR $= 7.1$ dB and SNR $= 7.7$ dB for NLoS and LoS links, respectively.

In literature, comparable results for simulations based on measured channels are found, although corresponding to SM on four transmit antennas.

A BER of 10^{-3} is obtained at approximately 11.5 dB SNR for a 4×4 link at 4 bit/s/Hz over a correlated channel, requiring a 2 to 2.6 dB larger SNR compared to our 2×4 measurement at 2 bit/s/Hz.

The performance of a 4×4 link at 3 bit/s/Hz for measured channels is documented in [8], obtaining a BER of 10^{-3} at an SNR of 12 dB and 18 dB for NLoS and LoS, respectively. The much higher SNR required for the LoS link is due to the high channel correlation, which is not the case for the off-body scenario, thanks to the isolation between front and back antennas caused by body shadowing.

V. Discussion

A comparison of the performance for the different 2 bit/s/Hz transmission schemes for the MIMO links in NLoS and LoS propagation environments at BER $=10^{-3}$ indicates that SM performs 3.5 to 5 dB better than SMX, and 2.8 to 4.3 dB worse than STC for the 2×2 links. For the 2×4 link, SM performs 2 to 2.6 dB better than SMX and 1.8 dB worse than STC.

SM is clearly a useful modulation scheme for off-body communication, especially in a 2×4 MIMO configuration. Although STC already provides an equal BER at 1.8 dB lower SNR, we note that an STC transmitter requires two full QAM transmit chains, whereas the SM transmitter only needs one transmit chain with a simple (non-quadrature) phase modulator and an RF switch connecting the antennas. The reduced complexity of the SM hardware motivates the choice of Spatial Modulation for off-body communications.

SMX requires an SNR that is 2 to 5 dB higher than for SM. The performance of SMX is degraded due to the negative correlation between front and back transmit antennas, each transmitting independent data streams in a scenario where one signal is often much stronger than the other.

In case of non-perfect channel estimates, the ML receiver cannot always simultaneously detect both transmitted symbols correctly. In contrast, when one signal is much weaker than the other in SM, the transmit antenna is readily detected and 50% of the modulated symbols are transmitted by the antenna corresponding to the strongest channel. The symbols transmitted via the weakest channel are not influenced by interference from another data stream, as is the case in SMX.

The system can readily be extended to multiple transmit antennas, providing more channel capacity. For body-centric communications, four separate antennas can be employed, mounted on the front, back, left and right shoulder, to achieve a channel capacity of 3 bit/s/Hz using BPSK modulation. If these antennas are dual polarized, switching between 8 different antenna feeds is a realistic option, adding 3 extra information bits to the modulation employed.

VI. Conclusions

The experimental transmissions at channel capacities of 2 bits/s/Hz presented in this paper indicate that Spatial Modulation is an interesting transmission scheme for low-cost off-body communication in LoS as well as NLoS environments when employing receiver diversity. Spatial Modulation performs significantly better than Spatial Multiplexing in all measured scenarios, and only 1.8 dB worse than Space-Time Coding in the 2×4 link. Importantly, the performance of Spatial Modulation is obtained at a significantly reduced hardware complexity at the transmitter, as only a single transmit chain is necessary, composed of a single modulator, a power amplifier and a switch for the whole system. For Spatial Modulation in BPSK at 2 bits/s/Hz, the modulator can be a single analog multiplier. In contrast, Space-Time Coding requires QPSK transmission to achieve the same channel capacity, requiring two power amplifiers and two complex-plane IQ-modulators. Therefore the proposed system provides an extremely low-cost solution for 2 bits/s/Hz off-body transmissions using front and back antennas. The system can readily be extended to a 4-antenna transmitter, operating at 3 bits/s/Hz by employing a 4-way switch. A further increased channel capacity is possible at a limited cost by using higher-order signal constellations.

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